Three Dimensional PIC Simulations of Novel Cathodes in the Michigan and AFRL Relativistic Magnetrons

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Abstract

Several novel shaped cathodes for a relativistic magnetron were modeled and optimized using a massively parallel electromagnetic particle-in-cell code ICEPIC. The effect of using a shaped cathode to enhance key performance parameters such as output power, power efficiency and impedance, was examined. In simulations we saw a dramatic increase in the range of magnetic field in which the magnetron functions, an increase of output power, an increase in efficiency, an elimination of mode competition, and immediate start up.

I. INTRODUCTION

Relativistic magnetrons can achieve an output power of hundreds of mega-watts. As such they have drawn the attention of the Department of Defense (DoD) as an effective source for delivering directed high power microwave radiation on target. Because it has not undergone the decades of refinement for output efficiency and power that has benefited conventional magnetrons, typical laboratory peak efficiencies (ratio of radiated energy to input electrical energy) are between 10-30 %. Thus, the design clearly requires refinement and improvement.

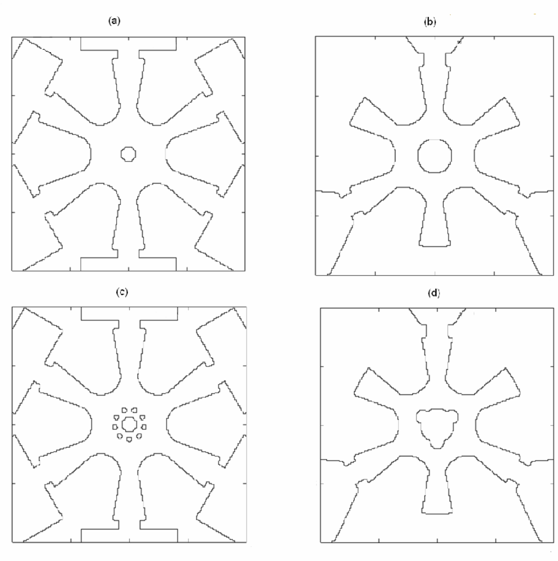

Fig. 1. (a) Standard Michigan Magnetron (b) Standard AFRL magnetron (c) 'Eggbeater' cathode in Michigan Magnetron (d) Shaped cathode in AFRL Magnetron.

II. METHOD

Our relativistic magnetron design modifications are done with the help of ICEPIC, short for Improved Concurrent Electromagnetic Particle-In-Cell code. ICEPIC was designed specifically to run on modern parallel computers [1]. ICEPIC solves Maxwell's equations and the relativistic Lorentz force law in the time domain. ICEPIC uses a fixed staggered grid to difference both Faraday's and Ampere's law, a technique developed by Yee [2]. ICEPIC employs "macro-particles" to represent the multitude of charged particles present in the magnetron, where one particle on the computer models a much larger number of particles which would be present in the experiment. The momentum and position of each charged particle is updated via the relativistic Lorentz force law using the Boris relativistic particle push algorithm [3]. Velocity and position are updated via the leapfrog method. These new velocities and positions allow a new current density and charge density to be determined, using the charge conserving current weighting algorithm of Villasenor-Buneman [4]. The solution process is then repeated.

The relativistic magnetron achieves optimum power efficiency when operating in the π mode. Operation in the π mode to the exclusion of all other modes means noise reduction and thus, a reduction in wasted energy [5]. Moreover, for pulsed powered magnetrons it is desirable to lock into the π mode as quickly as possible so that the time limited energy source is efficiently utilized. The major objective of the research presented here is developing a relativistic magnetron that has these desirable characteristics.

The standard design has undergone extensive testing both in the lab and numerically via ICEPIC. Experimental results on the A63 relativistic magnetron yield several performance trends. Among these are a specific voltage corresponding to a peak efficiency, a maximum efficiency of ~30% and a failure to oscillate above an axial magnetic field of 2.6 kilo Gauss (kG).

Numerical results indicate that the standard design suffers from excessive mode competition, long start-up times, failure to lock into the π mode and, for some parameters, failure to

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oscillate. To remove these performance deficiencies, we examine a new class of cathode, the geometrically primed cathodes (see figure 1).

Each of the novel cathodes examined here is designed to "prime" the magnetron to start oscillating quickly and to oscillate only in the π mode. We shall examine the three novel designs, Shaped Cathode, Eggbeater and Transparent, in turn.

We use ICEPIC to simulate, in 3D, the entire magnetron device. A general parameter scan of the axial magnetic field and the input diode voltage (anode-cathode voltage) was done for both the standard and shaped cathodes. For the Air Force Research Lab (AFRL) magnetron we looked at a range of magnetic field values extending from 1.8 to 3.4 kG for the shaped cathode and 2.2 to 3.4 KG for the standard cathode. Usually the field was incremented by 0.2 kG. The standard Michigan Magnetron operated at a slightly higher magnetic field so our scan started at 2.4 kG and extended to 3.2 kG for all Michigan Magnetron simulations. For most magnetic fields, we scanned through input potentials ranging from 200 kV to 800 kV. All simulations were done at the ERDC Major Shared Resource Center on the Cray XT3. Each simulation was run on either 48 or 64 processors. Simulations of the AFRL A63 magnetron ran for 150 ns. This equated to 101,568 time-steps. Simulations of the Michigan Magnetron were run for 300 ns, which equaled 183,513 time-steps.

All AFRL A63 relativistic magnetron simulations presented here share the following characteristics. The entire inner axis region of the magnetron can emit charged particles, however, the electric field threshold for electron emission varies. For the axial extent of the cathode corresponding to the axial length of the slow wave structure, the emission threshold is reduced by two orders of magnitude. This simulates the emission properties of the annealed carbon-on-carbon cathode present in that portion of the magnetron.

Emission properties for the Michigan Magnetron differed slightly. Unlike the AFRL Magnetron, an annealed carbon-on-carbon cathode is not used in the laboratory so the emission threshold was uniform throughout; this includes both the center cathode and the strips (for the eggbeater and transparent designs).

In the lab, the magnetron radiates power radially outward via the extraction ports and waveguides located 120 degrees from each other (see figure 1). An electromagnetic radiation absorbing boundary condition (Perfectly Matched Layer, PML) in each of the three waveguides simulates the radiation escaping from the magnetron. All simulations are carried out at a resolution of one grid cell length equals 1 mm.

III. Results

We first examine a single case where the shaped and standard cathodes are both allowed to operate at the same diode voltage and the same magnetic field. For this fiducial case we examine the configuration where the axial magnetic field is set at the value 2.4 kG, and the input voltage is set to approximately 400 kV. Key considerations in our evaluation of these cathode designs are efficiency, output power, mode selection, mode purity, and time to start microwave production.

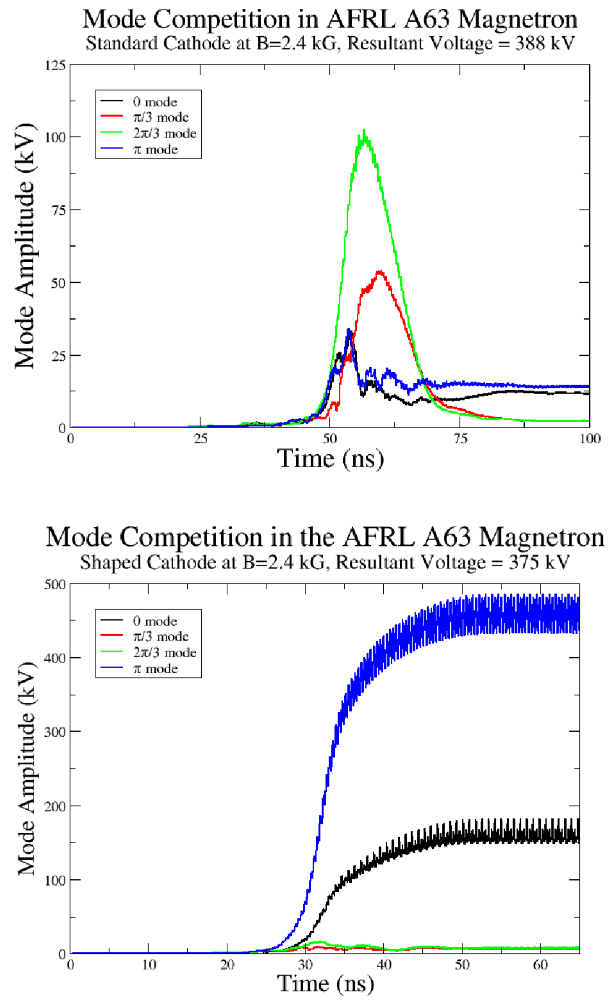

Fig. 2 Mode competition for the (a) standard cathode and the (b) shaped cathode.

Figure 2(a) shows mode evolution in time for both the standard and shaped cathodes. Upon the end of the voltage ramp up (50 ns) the standard cathode operates in the undesired 2π/3 mode. However, this is a transient period of dominance. By 75 ns, a low amplitude π mode, along with the *m=0* mode, emerge as the largest amplitude modes, with non-negligible competition coming from the π/3 and 2π/3 modes. These results stand in contrast to the mode plots produced by the shaped cathode simulation (figure 2 (b)). Not only does the π mode lock in immediately at 50 ns at 1.24 GHz, but its amplitude is 30 times greater than that produced by the standard cathode. Mode competition is significantly reduced with only the *m=0* "breathing" mode being present; even so, this mode is dominated by the π mode by a factor of three. The π/3 and 2π/3 modes are practically non-existent. Significant mode competition has been eradicated.

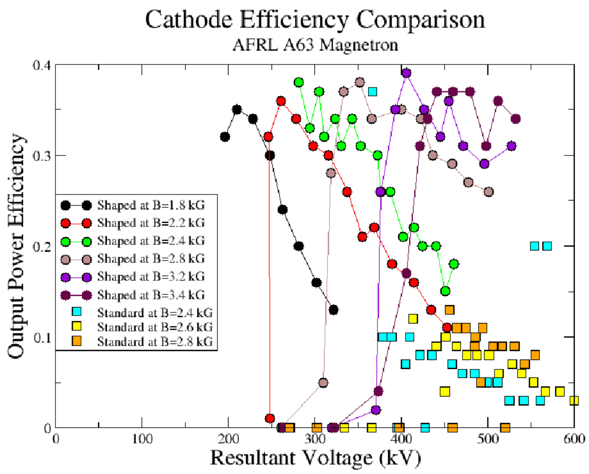

Fig. 3 Higher efficiency for the shaped cathode

The strong presence of the breathing mode is due to the way that we are extracting electromagnetic energy from the magnetron. Alternating cavities allow for the radiation of energy. This means that non-radiating cavities will have a higher energy density than those that radiate. This energy difference manifests itself as a non-traveling oscillating mode.

Output power and efficiency are also greatly affected by this design change. The efficiency of the shaped cathode saturates at 26 % in our fiducial case. This value is over three times that of the standard cathode. Of course, the efficiency increase is evident in the output power, where the addition of the shaped cathode results in a 5-fold increase in radiated power over the standard design. An examination of the upstream input current for both the standard and shaped cathodes reveals that the shaped cathode is drawing more current than the standard cathode (8 kilo Amps (kA) for shaped, 6 kA for standard). Since the downstream loss current is the same for both simulations (1.6 kA), this means that, for a given voltage, the shaped cathode is able to draw more power and use it more efficiently than the standard design.

Dramatic results are obtained for higher magnetic fields. We find that for all magnetic fields at, and greater than 2.8 kG, the standard cathode completely fails to oscillate. For all our input potentials (200 kV-800 kV), there is no appreciable output radiation. The situation is significantly different when the shaped cathode is used at these high magnetic field values. For example, with the shaped cathode at 550 kV input voltage and magnetic field at 3.4 kG, we again see a fast lock in of the π mode (at 50 ns), a lack of mode competition, a slight increase in π mode amplitude over the shaped cathode at 2.4 kG, and an increase in efficiency to 36%.

The results of our scan through magnetic field values indicate that there is a critical voltage for each magnetic field at which oscillations start to occur. This alone is not surprising; it is consistent with standard magnetron theory. This critical voltage also exists for the standard cathode but only at lower magnetic fields (2.2 kG – 2.6 kG). What is surprising, is that the shaped cathode produced π mode oscillations for all magnetic fields surveyed. Moreover, regardless of the magnetic field, the maximum efficiency that the shaped cathode obtained across our voltage scans was between 35-40%.

Figure 3 indicates that the shaped cathode creates a substantial increase in efficiency, as compared to the standard cathode at comparable magnetic fields. For example, at 2.8 kG, the maximum efficiency of the shaped cathode is about 38% at 350 kV, whereas the peak efficiency of the standard cathode is only about 13% at 450 kV. This is because most standard cathode simulations produced oscillations that were plagued by mode competition or no dominant mode at all. For high magnetic field values, (greater than 2.8 kG), we do not plot the results of the standard cathode since, as noted above, it failed to oscillate. This graph shows how robust the shaped cathode is. Oscillations were produced at all magnetic fields surveyed. The result that the shaped cathode produces oscillations at high magnetic field is important because higher magnetic field allows for higher output power. More importantly, however, is the expansion of the parameter space that the magnetron is now able to operate in. With the shaped cathode, the window of operations expands from 2.0-2.4 kG to at least 1.8-3.4 kG.

Several particle and field animations of the AFRL with shaped cathode have been made. These animations show that the magnetron is oscillating in an unexpected manner. Typically, a standard magnetron oscillates with a series of charged particle spokes rotating about the cathode. Our animations for the shaped cathode show that during the course of a single period, spokes are born primarily from the protrusions and migrate toward an extraction cavity, then dissipate one third of the way around the cathode as they collide with the particles located near the next protrusion. The collision seems to generate a vortex-like particle structure that then becomes a new spoke. Spokes do not seem to rotate about the cathode, rather they have a beginning, an end and a rebirth. This dynamic is more akin to a transit time oscillator than a standard magnetron. However, a review of our animations of the standard magnetron also revealed this behavior, but to a much lesser degree. It may be that the shaped cathode is amplifying a phenomena already present in the standard magnetron. We are investigating this further.

We next turn our attention to the “eggbeater” cathode design placed in the Michigan Magnetron. At a magnetic field of 3.2 kG, the eggbeater performs similarly to the shaped cathode in the AFRL magnetron. For example, at an input voltage of 300 kV, we observe π mode dominance at ~ 1 GHz, fast start-up, and negligible mode competition. These characteristics are representative of the eggbeater performance at 3.2 kG. Unlike the AFRL shaped cathode, there is no prominent breathing mode. However, as one scans through higher voltages, the breathing mode once again gains prominence until by 800 kV, its amplitude is 10% of the π mode amplitude. As with the shaped cathode in the AFRL A63 magnetron, a direct comparison with the standard cathode cannot be done because, at this high magnetic field value, simulations of the standard cathode failed to oscillate.

The efficiency obtained for our 300 kV, 3.2 kG case is 41%, with an output power of about 550 MW. This is a two-fold increase in output power compared to laboratory data for these voltage and field parameters [6]. Moreover, as we increase the input potential, we find that the output power exceeds a Gigawatt at 440 kV.

For most input voltages, eggbeater efficiency lies between 20-40 %. Yet for voltages less than 350 kV, efficiencies reach the mid 40% range. This trend toward higher efficiencies for lower input voltages holds true for magnetic fields of 3.0 kG, 2.8 kG as well. Of course, the peak efficiencies do decline rapidly as the magnetic field is lowered. Peak efficiency goes from 46% at 3.2 kG to 27% at 2.8 kG. These yield output powers of approximately 500 MW.

Unfortunately, these performance enhancements are no longer present when the magnetic field is reduced. Our parameter scans indicate that performance enhancement started to decline at a magnetic field of 2.6 kG. For example, a voltage scan at 2.4 kG reveals that the π mode is no longer preferentially selected, rather, it is the 2π/3 mode that is dominant. This is true despite analysis indicating that the π mode is still available for occupation at these parameters. Additionally, we find that mode competition is no longer mitigated. A typical mode amplitude spread at 2.4 kG shows that the breathing mode, π/3, and π mode at 34%, 15% and 6%, respectively, of the 2π/3 mode. Of course, this level of mode competition is accompanied by a corresponding reduction in efficiency. The median efficiency for a voltage scan at 2.4 kG is 6%.

Animations of the particle motion in the eggbeater cathode operating at 3.2 kG reveal a more conventional manner of oscillation. Unlike the shaped cathode, the spokes remain coherent throughout the oscillation of the magnetron; yet, the animations also show the presence of a significant migration of particles away from the cathode shortly before the approach of an oncoming spoke. The resulting interaction is not strong enough to disrupt the spoke but a similar collisional process in the shaped cathode was observed and, as mentioned above, severely disrupted the particle spoke.

The Transparent cathode performed similarly to the Eggbeater. Fast π mode lock-in and dominance, as well as high efficiency (on average near 30%), were characteristic of the voltage scans performed at 2.8 and 3.2 kG. However, at 2.4 kG, these features had vanished. The 2π/3 mode dominated with a high degree of mode competition and efficiencies were below 10%. The removal of the center cathode did not seem to enhance or diminish magnetron performance.

IV. Conclusion

According to ICEPIC simulations, these magnetron cathode augmentations may yield tremendous performance benefits, however, they have yet to be tested in the lab. The shaped cathode design will be the first to undergo extensive testing in the A63 AFRL magnetron starting this fall.

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